PROPOSAL AND DESIGN OF COMPACT OPTICAL DEVICE USING GRATING LENS FOR SPECTROSCOPIC IMAGING

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Abstract:

An optical device including planar grating and fiber bundle was proposed and designed for compact spectroscopic imaging system. Curvature of end face of fiber bundle and phase shift function of grating were optimized for reducing aberration. Spectral resolution of 4 nm with spatial resolution of 0.2 mm was predicted for 100 nm wavelength range with 10 mm bundle width.

1. Introduction

Spectroscopic imaging is useful technique in applications such as coloring-matter identification in old paintings or textiles, medium or chemical-state analysis in biological or medical diagnosis, etc. Although there have been several optical systems, a compact and handy system will be required in application to in situ analysis or in vivo diagnosis. A typical system, in which two-dimensional images are wavelength-filtered while many filters for different wavelengths are used in turn, is not good at detection of continuous spectra. Wavelength scanning of light-source by a monochromator can not be utilized in luminescence or wavelength shift case. Fourier transform spectroscopic imaging technique serves as a high performance system but requires some large optical system and complicated data conversion. On the other hand, a thin film grating lens[1-4)] is very attractive in system miniaturization since wavelength dispersion function and lens function can be achieved by single component. Besides it, a thin film grating can be fabricated by using planar fabrication processes with high productivity. However, a grating lens is not good at wide-view-angle imaging, because large aberration arises when the grating is used with neither designed incident wavefront nor designed wavelength. Specially designed systems are therefore required for suppressing aberration down to practical level. For an example, we reported[5)] a combination of two gratings, one for mainly color-splitting and the other for mainly aberration correction, to construct a compact color scanner system where it is sufficient to detect only three colors. In this paper, we propose and discuss a new compact optical device applicable to two-dimensional mapping of continuous spectra.

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2. Configuration of proposed optical device

Reflection, transmission or luminescence spectra of a subject are detected by using a fiber bundle, a thin film reflection type grating and a two-dimensional image sensor. Light from the subject is coupled into the fiber bundle through an input end, and is guided to an output end. Schematic view of the proposed compact spectroscopic imaging device is illustrated in Fig. 1. End surface of the fiber bundle is curved horizontally. A curved mask with a thin slit is set close to the bundle end surface with small gap. Light, coming out through the silt and diverging in the air, is diffracted by the grating lens to the image sensor. Diffraction angle depends on wavelength. The grating lens is designed so that light from one fiber end is focused onto a corresponding focal line dispersed with wavelength along y_P-axis on the image sensor plane. Spectrum of the light is given by intensity distribution along y_P-axis on the image sensor. Lights from the center fiber end O and the most outside fiber end Q and their spectra are also shown in Fig. 1 as typical examples. Thus spectrum distribution along a fiber array on the slit are obtained at the same time by detecting two-dimensional intensity distribution on the image sensor. By moving the fiber bundle vertically and by detecting spectrum distribution of different fiber arrays one another, we can obtain two-dimensional spectrum mapping of the light guided in the fiber bundle.

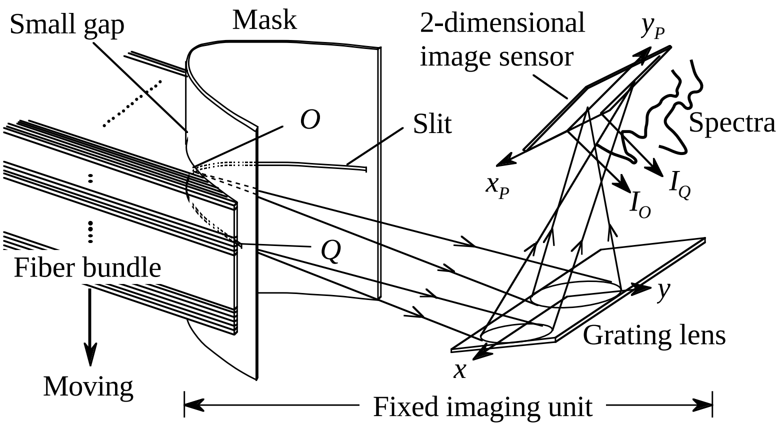

Fig. 1 Schematic view of proposed compact spectroscopic imaging device.

3. Design of grating lens and fiber end position

A device was designed for fiber bundle of 10 mm width and spectrum range from 510 nm to 610 nm with resolution better than 5 nm this time. This system would be useful for ischemia diagnosis since the spectrum range and resolution is used in blood oximetry. Cross sectional view of optics layout is depicted in Fig. 2. Angle θ_{IN} of incident wave to the grating was 70˚. Propagation direction of diffracted wave depends on wavelength but was almost normal of the grating surface. These were chosen to give large wavelength dispersion in diffraction angle with practically feasible optics layout. Numerical aperture of each fiber was assumed to be 0.05.

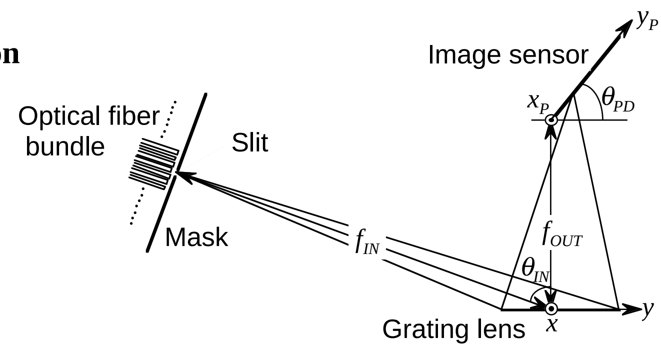

Fig. 2 Cross-sectional view of optics layout and waves on y-z plane.

Position of each fiber end on the slit, phase shift function of the grating, and tilt angle θ_{PD} of the image sensor plane measured from parallel to the grating plane are optimized by numerical iteration using ray tracing method for minimizing the largest aberration in foci on the image sensor plane for incident waves of wavelengths of 510 nm, 560 nm and 610 nm radiated from fibers located at $x = 0$, ±1, ±2, ±3, ±4, ±5 mm. Phase shift function of the grating was expressed by

$$\Phi = \frac{2\pi}{\lambda_D}\left\{\sqrt{x^2+\left(y+f_{IN}\sin\theta_{IN}\right)^2+\left(f_{IN}\cos\theta_{IN}\right)^2}+\sqrt{x^2+y^2+f_{OUT}{}^2}+\sum_{i=0}^{8}\sum_{j=0}^{8-i}C_{ij}x^i y^j\right\}, \qquad (1)$$

where λ_D was a wavelength used only in numerical procedure and was 560 nm. The first and the second terms in braces represent phases on the grating plane of an incident wave diverging from a point (0, - f_{IN} sin θ_{IN}, f_{IN} cos θ_{IN}) and of a diffracted wave focusing to a point (0, 0, f_{OUT}). Lengths f_{IN} and f_{OUT} were used as initial values in numerical optimization and both were 10 mm. A grating of which phase shift function consists of only the first and the second terms provides an aberration-free focus for the above-mentioned incident wave of wavelength λ_D. However, the aberration grows when an incident wave deviates in wavelength or in wavefront from the designed one. The third term consisting of polynomials with respect to coordinates was introduced to reduce the aberration down to acceptable level for any incident wave in consideration. Coefficients C_{ij} were optimized along with the tilt angle θ_{PD} and the fiber end position. m-th line pattern of the grating lens which gives the phase shift was calculated from $\Phi = 2\pi m$ + const. The grating can be fabricated by the electron beam direct writing technique.

Optimized fiber end position is traced in Fig. 3. Distance from the grating is the longest at the center and becomes shorter for a fiber situated farther from the center. It ranges from 7.5 mm to 21 mm. Such a deeply concave form makes sense in view of well known configuration for sharp imaging with plane surface. Tilt angle θ_{PD} was optimized to be 51˚. This rather large angle results from a fact that lens power becomes weaker for shorter wavelength while the diffraction angle is smaller. Point spread images obtained by plotting points of sampled rays crossing the image plane are shown in Fig. 4. Coordinates x_P and y_P of the image plane are defined in Fig. 2. Three images on y_P-axis are for light coming from the center point O shown in Fig. 1. Top, middle and bottom images correspond to wavelengths of 510 nm, 560 nm and 610 nm, respectively. This indicates the spectrum is obtained by detecting intensity profile along y_P-axis even if it is continuous one. Images are dispersed over 25 mm for a wavelength range of 100 nm while root mean square (RMS) spot radius was calculated to be smaller than 0.05 mm, meaning spectrum resolution of 2 nm. Eleven sets of three images are shown for lights of the same wavelength

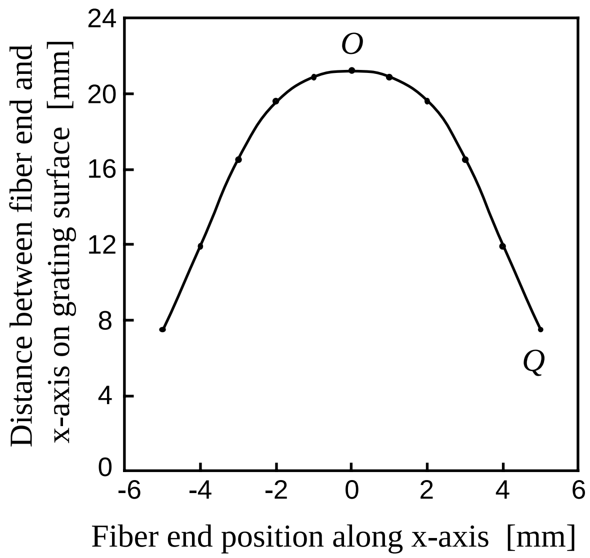

Fig. 3 Optimized fiber end position measured from x-axis on grating plane, showing mask curvature or slit curve.

set diverging from fibers situated at x = 0, ±1, ±2, ±3, ±4, ±5 mm. The largest RMS spot radius was included in the end image set Q, but smaller than 0.1 mm. Spectrum is spread over 3.5 mm, meaning the resolution is better than 4 nm. Spatial resolution along x-axis was estimated to be 0.2 mm from RMS image radius and spaces between the image sets and between corresponding fibers. Spectrum line is slightly tilted from y_P-axis and data processing is required to give a correct spectrum for light from an outer-side fiber situated at |x| > 4 mm, whereas spectrum line for an inner-side fiber is almost parallel to y_P-axis and the spectrum can be obtained directly from intensity distribution on a raster if a usual two-dimensional CCD is set on the image plane.

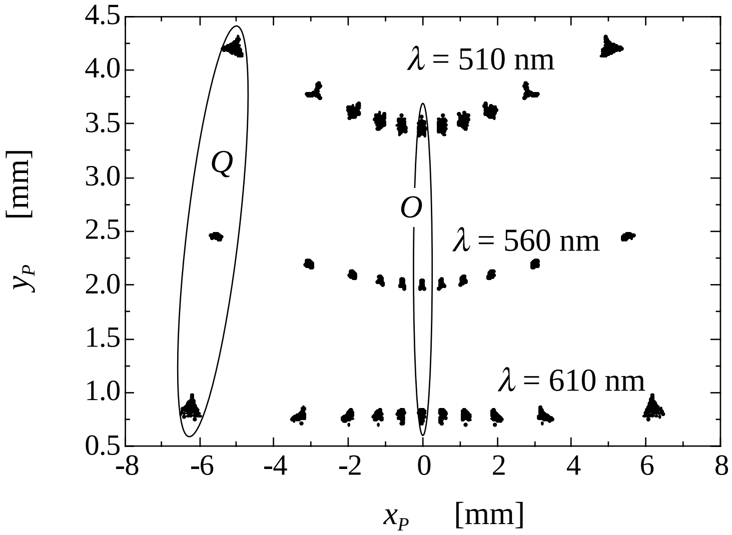

Fig. 4 Point spread images obtained by ray tracing. Image sets of O and Q are for lights from points O (x = 0) and Q (x = 5mm) depicted in Figs. 1 & 3, respectively.

4. Conclusion

A new configuration was proposed and designed for constructing a compact spectroscopic imaging system. Phase shift function of reflection grating lens, curvature of fiber bundle end face and tilt angle of imaging plane were optimized for suppressing aberration down to practical level. Spectral resolution of 4 nm with spatial resolution of 0.2 mm is expected for 100 nm wavelength range with 10 mm fiber bundle width.

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